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Detection of Nonthermal Continuum Radiation in Saturn's Magnetosphere

by

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ABSTRACT

A detailed analysis of high resolution wideband data from the Voyager 1 and 2 plasma wave receivers has revealed the presence of heretofore undiscovered nonthermal continuum radiation trapped within the Saturnian magnetosphere. The discovery of Saturnian trapped continuum radiation fills a disturbing void in the Saturnian radio spectrum. On the basis of observations at both the Earth and Jupiter it was expected that continuum radiation should be a pervasive signature of planetary magnetospheres in general. Special processing of the Voyager 1 plasma wave data at Saturn has now confirmed the existence of weak emissions that have a spectrum characteristic of trapped continuum radiation. Similar radiation was also detected by Voyager 2; however, in this case it is not certain that Saturn was the only source. Considerable evidence exists which suggests that Saturn may have been immersed in the Jovian tail during the Voyager 2 encounter, so that Jupiter may provide an additional source of the continuum radiation detected by Voyager 2.

I. INTRODUCTION

A preliminary survey of the Voyager 1 plasma wave observations at Saturn yielded no evidence for trapped, nonthermal continuum radiation [Gurnett et al., 1981a,b]. Scarf et al. [1982] reported no firm evidence for the presence of the radiation in the Saturnian magnetosphere during the Voyager 2 encounter. The absence of this emission from the Saturnian radio spectrum had left a situation somewhat difficult to understand in view of the pervasive presence of the trapped radiation in both the terrestrial and Jovian magnetospheres [Gurnett, 1975; Gurnett et al., 1980]. Gurnett et al. [1981b] suggested that although the magnetospheric cavity at Saturn, which has regions with electron plasma frequencies well below that in the solar wind, was suitable for trapping electromagnetic radiation, perhaps the emission source did not extend to sufficiently low frequencies to illuminate the cavity.

We have carefully re-examined the Voyager plasma wave observations and now have evidence for the existence of electromagnetic radiation in the Saturnian magnetosphere similar to trapped continuum radiation at the Earth and Jupiter. We shall first present the observations of the continuum radiation and compare the emission with the terrestrial and Jovian counterparts. Then we shall address the question of the source of the emission observed by Voyager 2. Since it is possible that the Saturnian magnetosphere was imbedded in the Jovian tail during the second encounter, it is equally possible that some of the radiation detected by Voyager 2 had its origin at Jupiter.

II. OBSERVATIONS OF TRAPPED CONTINUUM RADIATION AT SATURN

Figure 1 shows an example of diffuse electromagnetic radiation which we identify as trapped, nonthermal continuum radiation. In the bottom panel, a high resolution frequency-time spectrogram is shown. In this display, wave intensity is plotted as a function of frequency (ordinate) and time (abscissa) with the darkest areas representing the most intense waves. The continuum radiation appears between about 500 Hz and 3 kHz as a relatively weak, broadband emission. We do not think the sporadic nature of the emission *is real*; we *attribute* the effect to the automatic gain control circuitry in the receiver. The intense band near 300 Hz appears in all the wideband spectra recorded during the encounter and is thought to be identified with the operation of the spacecraft's tape recorder. The narrowband tone at 2.4 kHz is interference at the power supply frequency.

More details of the continuum radiation spectrum can be seen in the 4-sec average spectrum shown in the upper panel of Figure 1. The emission shows a smooth rolloff at lower frequencies with a cutoff at about 500 Hz. The plasma density at this time is about 2 to 3 $\times 10^{-3}$ cm^{-3} [Bridge et al., 1981], hence the electron plasma frequency is in the range of 400 to 500 Hz. (The electron plasma frequency, f_p^-, is related to the electron density, n_e by $f_p^- = 8980\sqrt{n_e}$ where f_p^- is in

Hz and n_e is in cm^{-3}.) The magnetic field strength, B, is about 6 nT [Ness et al., 1981] giving an electron gyrofrequency, f_g^-, of about 170 Hz. ($f_g^- = 28B$ with f_g^- in Hz and B in nT.) The lower frequency cutoff of the emission, then, is near f_p^- and is well above f_g^-, hence, this must be a free-space electromagnetic mode. The higher frequency portion of the radiation's spectrum shows a spectral index of about -3. (The dip in the spectrum at 2.4 kHz is the effect of a notch filter in the receiver designed to attenuate the power supply interference.) This spectral index can be compared to continuum radiation trapped within the Earth's magnetosphere which shows a frequency dependence ranging from f^{-3} to f^{-6}. Gurnett et al. [1980] report that Jovian continuum radiation has a frequency dependence of $\sim f^{-4}$, and a detailed analysis of the spectral index of several Jovian continuum radiation spectra shows a wide range of variability about -4 similar to the Earth.

Another example of trapped continuum radiation detected in Saturn's magnetosphere is shown in the right-hand panel of Figure 2. This example was taken by Voyager 2 on its outbound trajectory at a distance of 51.0 R_S. The left-hand panel of Figure 2 is data taken very close to Jupiter in the dayside lobe region. A comparison of these two spectrograms shows the remarkable similarity in the continuum radiation detected at Jupiter and Saturn. The major difference in these two frames is the absence of spacecraft interference near 2 kHz in the Jupiter frame. The Jovian radiation is much more intense relative to the interference and, as a result, the interference is not observable.

Figure 3 offers a more detailed comparison of the two spectra shown in Figure 2. These are 4-sec average spectra plotted on a logarithmic frequency scale. In this figure, the differences in the spectra below ~500 Hz can easily be seen. The Saturn data contains an intense band of noise between 60 and 500 Hz; this is consistently seen in the Voyager 2 Saturn data and is thought to be caused by the tape recorder on board the spacecraft. The tape recorder was not on during the Jupiter frame (left panel) and the noise is not present, however, an intense, narrowband emission is seen at about 300 Hz. Little is currently known about this band except that it is probably electrostatic and may be responsible for the generation of the very low-frequency continuum radiation detected in the tail lobes at Jupiter.

The broadband noise characteristics above ~500 Hz in both spectra are very similar. Both show a frequency dependence of about f^{-4} as indicated by the dashed lines in the figure. The near-Jupiter spectrum appears to have some banded enhancements near 1 kHz, but these are probably due to the close proximity of Voyager to the source of the radiation, as has been noted by Gurnett et al. [1979]. The Voyager 2 spectrum in the right-hand panel of Figure 3 is very similar to Jupiter spectra shown by Gurnett et al. [1980] as well as those shown by Gurnett [1975] and Kurth et al. [1981a] for terrestrial, trapped continuum radiation.

If we assume the broadband emission shown in the right-hand panel of Figure 3 is trapped continuum radiation, then the local electron plasma frequency given by the cutoff at ~600 Hz implies a density of 4.5×10^{-3} cm^{-3}. This is compared to an electron density determined by the plasma investigation of about 5×10^{-3} cm^{-3}. Since the magnetic

field is about 2 nT here [Ness et al., 1982], the electron gyrofrequency is ~56 Hz and, hence, is much less than f_p^-. The waves above 600 Hz, then, must be freely propagating electromagnetic waves, consistent with the hypothesis that they are continuum radiation. (Kurth et al. [1981b] examined in detail the possibility that the radiation we identify as continuum radiation might be thermal electrostatic noise in the ambient plasma [Hoang et al., 1980] and concluded that the Voyager observations could not be explained by that mechanism.)

Since preliminary surveys of the plasma wave observations at Saturn failed even to reveal the presence of trapped continuum radiation, it is clear that the emission reported herein is certainly not a dominant feature in Saturn's radio spectrum. The emission is readily observable in the spectrum analyzer data only between day 318 ~ 2130 and day 319 at ~ 0030 SCET during the Voyager 1 encounter, otherwise, the more sensitive waveform receiver must be used. However, the waveform receiver was interrogated only once every several hours so that the wideband data are available for only about 18 time periods between the first and last Voyager 1 magnetopause crossings during the times when the spacecraft was beyond the inner magnetosphere (where other strong emissions dominated). Of these 18 interrogations, only three between 1446 SCET on day 318 and 0541 SCET on day 319 showed any evidence of trapped continuum radiation. During this time period, Voyager 1 traveled from about 17 R_S to 32 R_S at northern latitudes between about 15° and 21° on the outbound leg (~ 3 hours local time). During the Voyager 2 encounter there were 12 waveform receiver interrogations in the outer magnetosphere and five showed evidence of trapped continuum radiation between about 1415 SCET on day 239 and 1940

SCET on day 240 as the spacecraft traveled between 29.5 R_S and 50.7 R_S at ~ −29° latitude (~ 5.5 hours local time). Because both spacecraft were relatively close to the equator on their respective inbound trajectories, it is quite probable that the failure to detect trapped continuum radiation on the dayside was due to plasma sheet densities being greater than or equal to the solar wind density, hence, no wave trapping could occur in the vicinity of the spacecraft. A comparison of the amplitudes of the Jovian and Saturnian radiation in Figure 3 shows two or three orders of magnitude difference in the spectral density at the same frequency. One of the Voyager 1 detections at Saturn was two orders of magnitude weaker still than the example shown in the right-hand panel of Figure 3. Because the waveform data is available infrequently it is difficult to properly compare the intensity of the emission between the two encounters. However, a comparison of the spectra shown in Figure 1 and the right-hand panel of Figure 3 show both Voyager 1 and 2 measured spectral densities near 3×10^{-14} $V^2m^{-2}Hz^{-1}$ at 1 kHz.

III. THE SOURCE OF THE RADIATION DETECTED BY VOYAGER 2: SATURN OR JUPITER?

It was first noticed by Scarf [1979] that the Voyager 2 cruise trajectory from Jupiter to Saturn would take the spacecraft through the nominal position for an extended Jovian magnetotail. During the same general time period Saturn would also pass through the downstream region and perhaps be immersed in the Jovian tail as well. Scarf went on to suggest it was possible for Saturn to be within the Jovian tail during the Voyager 2 Saturn encounter. Similar predictions have since been made by Grzedzielski et al. [1980]. Here we have reported the detection of trapped continuum radiation in the Saturnian magnetosphere and in this section we examine the question of whether the continuum radiation detected by Voyager 2 during its encounter was generated at Saturn only or could there possibly be a component arriving from Jupiter.

First, however, it should be clearly stated that the detection of trapped continuum radiation in Saturn's magnetosphere by the Voyager 1 plasma wave receiver is sufficient to unambiguously identify Saturn as a source of the emission. Voyager 1 had not detected Jovian continuum radiation since June 5, 1980 [Kurth et al., 1982] and there was no reason to expect Saturn to be influenced by the Jovian tail during the time of the first encounter. The Voyager 2 detections of continuum radiation must be interpreted with caution, however, since there is a significant amount of evidence consistent with a Jovian interaction. Indeed, the

presence of continuum radiation in the Saturnian magnetosphere during the encounter is a necessary condition if Saturn was inside the Jovian magnetotail during the Voyager 2 encounter.

Several of the initial reports of Voyager 2 observations at Saturn suggested that Saturn may have been imbedded in the Jovian tail during the encounter. The first indication of a possible Jovian influence was the extremely large size of the Saturnian magnetosphere observed during the outbound trajectory. The bow shock was approximately twice as distant from Saturn as was found with Voyager 1. Bridge et al. [1982] concluded that the magnetosphere could be expected to be this large only ~3% of the time based on a statistical study of the solar wind ram pressure. They mention the possibility that the extremely inflated magnetosphere might be caused by the influence of the Jovian magnetosphere. In fact, the statistical study performed by the plasma science team [Bridge et al., 1982], which gives a distribution of expected magnetosphere sizes on the basis of the past history of the ram pressure, included in its data set some time periods of suspected and known tail encounters. Hence, the very largest sizes predicted by that study may only be possible via tail immersion rather than abnormal solar wind conditions. Moreover, even if the solar wind pressure could drop by an amount sufficient to explain this large size, it is doubtful these conditions could exist for the 3 or 4 days required to account for the Voyager 2 observations. Immersions in the Jovian tail, on the other hand, can easily last for several days [Kurth et al., 1982; Scarf et al., 1981].

Scarf et al. [1982] and Warwick et al. [1982] both indicate that a surprising disappearance of the kilometric radio emissions for as much as four days following closest approach could be explained by the lack of charged particles entering the polar cusp from the solar wind as a consequence of being shielded from the solar wind by Jupiter's magnetotail. Kaiser et al. [1981] have identified the cusp as a likely source for the Saturnian kilometric radiation as a result of a statistical study of the emission's beam geometry and suggest enhanced precipitation down the cusp could generate the radio waves. Warwick et al. [1982] go on to say that Voyager 2, unlike Voyager 1, monitored several well-defined, dramatic decreases in kilometric radiation activity for periods of two to four days in the two months prior to the encounter, when Saturn was likely to be immersed in the Jovian tail.

Neither the magnetometer team nor the cosmic ray science teams suggest that Jupiter influenced the state of the Saturnian magnetosphere during the Voyager 2 encounter. However, both instruments recorded evidence of changing solar wind or external conditions near the middle of day 237 when Voyager was 10 to 20 R_S from Saturn on its inbound leg. The energetic particle fluxes showed evidence of strong influence from changing solar wind conditions between 0920 and 1630 [Vogt et al., 1982]. Ness et al. [1982] report changes in the magnetic field on day 237 which would correspond to a decrease in the solar wind ram pressure. Ness et al. also remarked that changes in the field in the outer magnetosphere observed by Voyager 1, which were probably the result of solar wind fluctuations, were noticeably absent during the Voyager 2 outbound leg.

Kurth et al. [1981b, 1982] have argued that low-frequency continuum radiation acts as a very good tracer for use in mapping the Jovian

magnetosphere and have provided observations of the extended magnetotail of Jupiter to nearly 9000 R_J downstream from Jupiter. Studies by Lepping et al. [1982] of the magnetic field configuration during periods when the low-frequency cutoff of the radiation extends to as low as 311 Hz (referred to as "core" regions) [Kurth et al., 1982] show signatures reminiscent of tail field configurations; these authors conclude that the cores are, indeed, encounters with the magnetotail surrounded by a magnetosheath-like region.

Figure 4 contains data from an event discussed by Kurth et al. [1982] recorded just upstream of the Saturnian bow shock at a distance of 35.3 R_S from Saturn. The narrow horizontal lines at 1.75 kHz, 2.4 kHz, and briefly at 400 Hz and odd harmonics are all spacecraft interference. The intense band below ~500 Hz is also spacecraft noise. The weak, diffuse noise with a low-frequency cutoff at about 3.5 kHz is non-thermal continuum radiation. The continuum radiation shown in Figure 4 compares very well with continuum radiation detected just 2019 R_J from Jupiter (see Figure 6 of Kurth et al. [1981b]). The low-frequency cutoff is presumed to be near the local electron plasma frequency, hence, n_e for the event in Figure 4 is about 0.15 cm^{-3}. This density is much larger than densities typically found in the actual Jovian magnetotail (or core events) discussed by Kurth et al. [1982], but it is similar to the density in the wake regions surrounding the core. The 'wakes' studied by Kurth et al. are low density regions surrounding the Jovian magnetotail filled by continuum radiation leaking out of the tail. Kurth et al. find no significant differences between the plasma characteristics in the wake and the nominal solar wind (other than low densities).

Lepping et al. [1982], however, suggest magnetosheath-like field configurations may be present in the wake immediately outside the core regions. The evidence presented in Figure 4, then, would seem to suggest that Voyager 2 and Saturn may have been in the Jovian wake just prior to the encounter.

The radiation shown in Figure 4 upstream of Saturn is unlike any of the continuum radiation detected within Saturn's magnetosphere. Since the solar wind plasma frequency near Saturn is typically 2-3 kHz and the spectral density has a f^{-3} to f^{-4} dependence, trapped radiation from Saturn cannot build up to detectable amplitudes at frequencies much above 1 kHz. Some radio emissions are observed at Saturn in the same frequency range as those in Figure 4, but they are extremely narrowbanded emissions which are similar to terrestrial escaping continuum radiation [Gurnett et al., 1981b]. We conclude, therefore, that the emission in Figure 4 is most likely Jovian continuum radiation.

There was another detection of continuum radiation prior to leaving the Saturnian magnetosphere for the final time, however, at this time Voyager 2 was located in the Saturnian magnetosheath [Bridge et al., 1982]. Figure 5 shows a spectrogram from day 241 when Voyager 2 was 64.7 R_S from Saturn. Here a very weak emission near 2 kHz can be seen between the two interference tones at 1.75 and 2.4 kHz. This noise seems to have a more sharply defined upper cutoff than the other spectra shown herein, however, there is a notch filter at 2.4 kHz which would attenuate a broadband signal and the spectrum would appear to have a cutoff below 2.4 kHz. We therefore believe this to be another example of continuum radiation. In this case, the low-frequency cutoff is at about 1.9 kHz corresponding to a density of 4.5×10^{-2} cm^{-3}. The density as measured

by the plasma science instrument for this time is $\sim 5 \times 10^{-2}$ cm^{-3}, and the agreement is excellent to within the accuracy of the measurements. This density is typical of a Jovian wake region as reported by Kurth et al. [1982].

In the previous section we described observations of trapped continuum radiation made by Voyager 2 within the Saturnian magnetosphere and compared the spectrum with Jovian continuum radiation. This comparison shown in Figures 2 and 3 shows remarkable similarities. In fact, the amplitude of the noise from day 240 is very close to what would be expected if this were a core region in Jupiter's tail. Kurth et al. [1982] reported voltage spectral densities in the core regions at about 7000 R_J from Jupiter near 2×10^{-12} $V^2m^{-2}Hz^{-1}$ at 562 Hz. Had the low-frequency cutoff been slightly lower in the right hand spectrum in Figure 3, the spectral density at 562 Hz would be near 10^{-12} $V^2m^{-2}Hz^{-1}$, which is comparable to the previous measurements of the intensity of the continuum radiation far downstream from Jupiter. Hence, we conclude that Jupiter is a possible source of the continuum radiation shown in the right-hand panels of Figures 2 and 3, as well as a probable source for the emission shown in Figures 4 and 5 observed just outside the Saturnian magnetosphere.

The observations presented herein show a surprisingly coherent sequence of continuum radiation measurements suggesting Voyager 2 was detecting Jovian continuum radiation from wake regions surrounding the extended Jovian tail just before entering the Saturnian magnetosphere on day 236 and just outside a highly inflated Saturnian magnetosphere on day 241. Deep within the Saturnian magnetosphere, on days 239 and 240, Voyager detected radiation which could be associated with the extended

Jovian magnetotail itself, having a spectrum similar to continuum radiation in near-Jupiter lobes and amplitudes consistent with radiation in the extended Jovian tail detected prior to the Saturn encounter, although we cannot be sure that this radiation is not generated entirely at Saturn.

These new observations fit in very well with other Voyager 2 observations suggesting Saturn may have been in the Jovian tail during the encounter. We contemplate the following scenario: just prior to entering the Saturnian magnetosphere, Voyager 2 and Saturn entered a wake region near the Jovian tail or tail filament. Magnetic field and energetic particle flux signatures detected near midday on day 237 suggest the external pressure dropped dramatically as the Saturnian magnetosphere entered the Jovian tail, proper. Almost simultaneously the Saturnian kilometric radiation disappeared for up to four days, in response to the fact that the polar cusp was shielded from the solar wind and precipitation down the cusp was suspended or reduced. During this several-day period the plasma wave instrument detected very low frequency continuum radiation from Jupiter which had propagated down the tail and spilled into the low-density portions of the Saturnian magnetosphere. The Saturn bow shock was finally traversed early on day 243. In the same time frame the radio emissions reappeared, with some of the most intense kilometric radiation activity of the post-Saturn leg occurring on day 243. Since leaving the Saturnian magnetosphere the continuum radiation has not been detected again (as of day 267, 1981).

IV. CONCLUSIONS

We have presented evidence in this paper for the existence of nonthermal continuum radiation trapped within the Saturnian magnetosphere. This discovery eliminates the necessity of explaining why Saturn is unlike the other planets in the solar system with well-developed magnetospheres which are pervasively filled with the low frequency radio emission. The discovery of trapped continuum radiation in Saturn's magnetosphere during the Voyager 2 encounter also provides a necessary condition for the presence of a Jovian interaction. Unfortunately, the inability to identify the source of the radiation leaves us without the evidence sufficient to decide the issue. Although we cannot give unambiguous evidence of an interaction between Saturn's magnetosphere and the extended Jovian tail, we believe the set of observations presented here coupled with effects already reported concerning the size of the magnetosphere and the disappearance of the kilometric radiation are entirely reasonable and self-consistent with the immersion of Saturn in the Jovian tail. If this is the case, this is the first *in situ* observation of a magnetosphere not under the direct influence of the solar wind and possibly the only one that will ever be obtained.

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FIGURE CAPTIONS

Figure 1 — A frequency-time spectrogram (lower panel) and a 4-sec average spectrum (upper panel) showing the characteristics of continuum radiation trapped within the Saturnian magnetosphere.

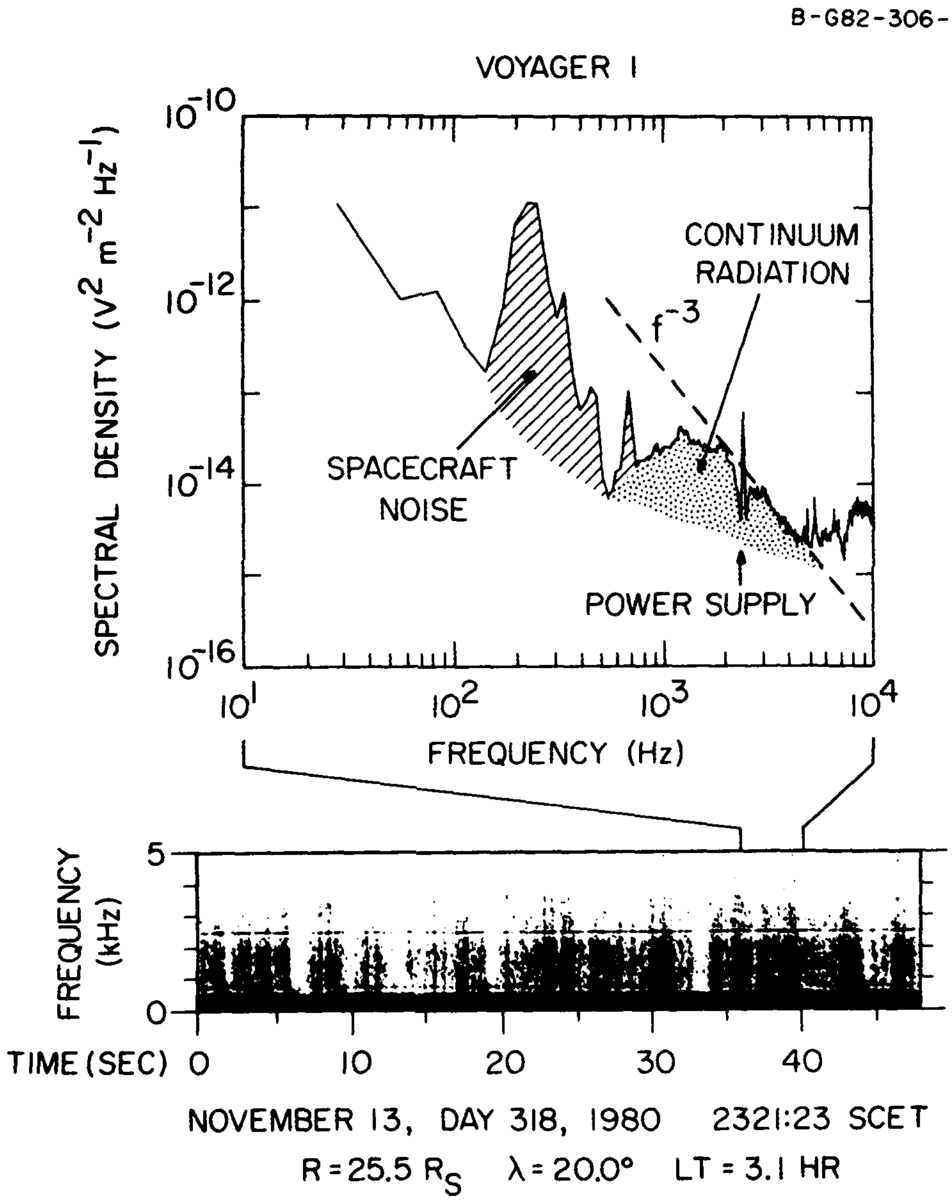
Figure 2 — Spectrograms comparing continuum radiation in the near-Jupiter lobe (left-hand panel) with a similar emission detected when Voyager was in the Saturnian ma etosphere at a distance of 51 R_S (right-hand panel).

Figure 3 — A detailed comparison of 4-sec averages of the spectra shown in the previous figure demonstrating the similarity of the broadband noise seen near Saturn on day 240, 1981 (right-hand panel) and that detected in the near-Jupiter lobe on day 188, 1979 (left-hand panel).

Figure 4 — A frequency-time spectrogram showing diffuse continuum radiation above 3.5 kHz. The presence of this noise implies the spacecraft is in the wake of the

distant Jovian tail. At this time Voyager was just upstream of the Saturnian bow shock 35.3 R_S from Saturn.

Figure 5 A final detection of continuum radiation before Voyager 2 had left the Saturnian magnetosphere for the last time. Here the spacecraft is 64.7 R_S from Saturn.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R = 25.5 R_S λ = 20.0° LT = 3.1 HR

Figure 1

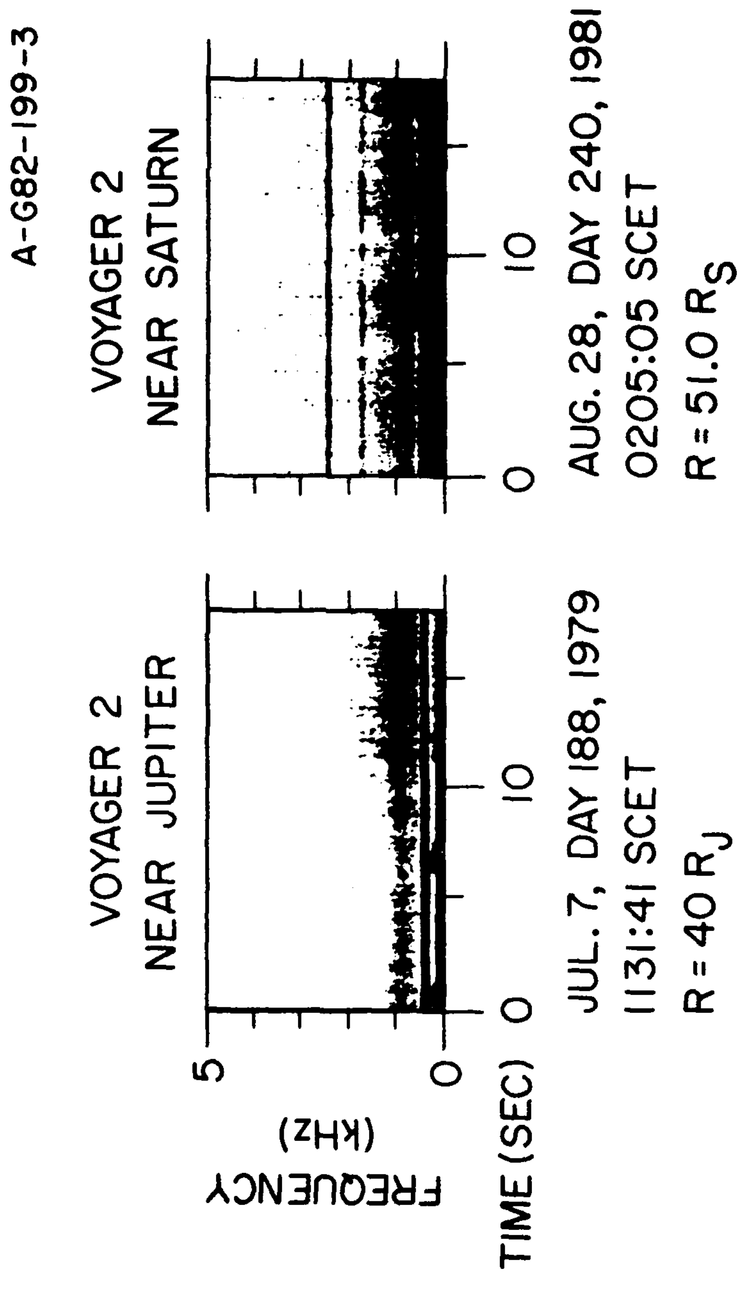
A-G82-199-3
VOYAGER 2
NEAR JUPITER
VOYAGER 2
NEAR SATURN
FREQUENCY
(KHz)
5
0
TIME (SEC)
0
10
0
10
JUL. 7, DAY 188, 1979
1131:41 SCET
R = 40 R_J
AUG. 28, DAY 240, 1981
0205:05 SCET
R = 51.0 R_S

Figure 2

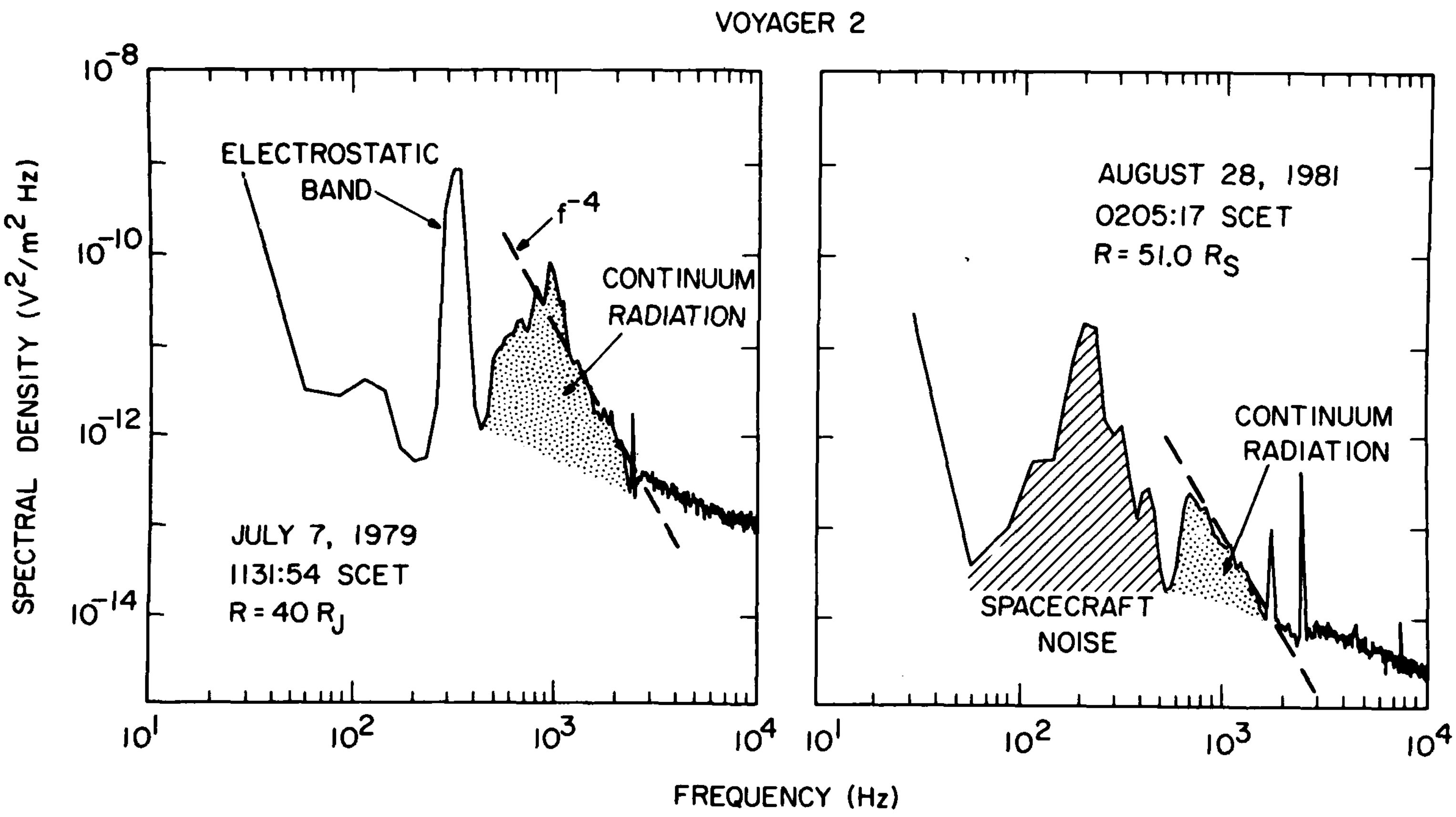
VOYAGER 2
ELECTROSTATIC
BAND
f^{-4}
CONTINUUM
RADIATION
JULY 7, 1979
1131:54 SCET
R = 40 R_J
AUGUST 28, 1981
0205:17 SCET
R = 51.0 R_S
CONTINUUM
RADIATION
SPACECRAFT
NOISE
SPECTRAL DENSITY (V^2/m^2 Hz)
FREQUENCY (Hz)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^1
10^2
10^3
10^4

Figure 3

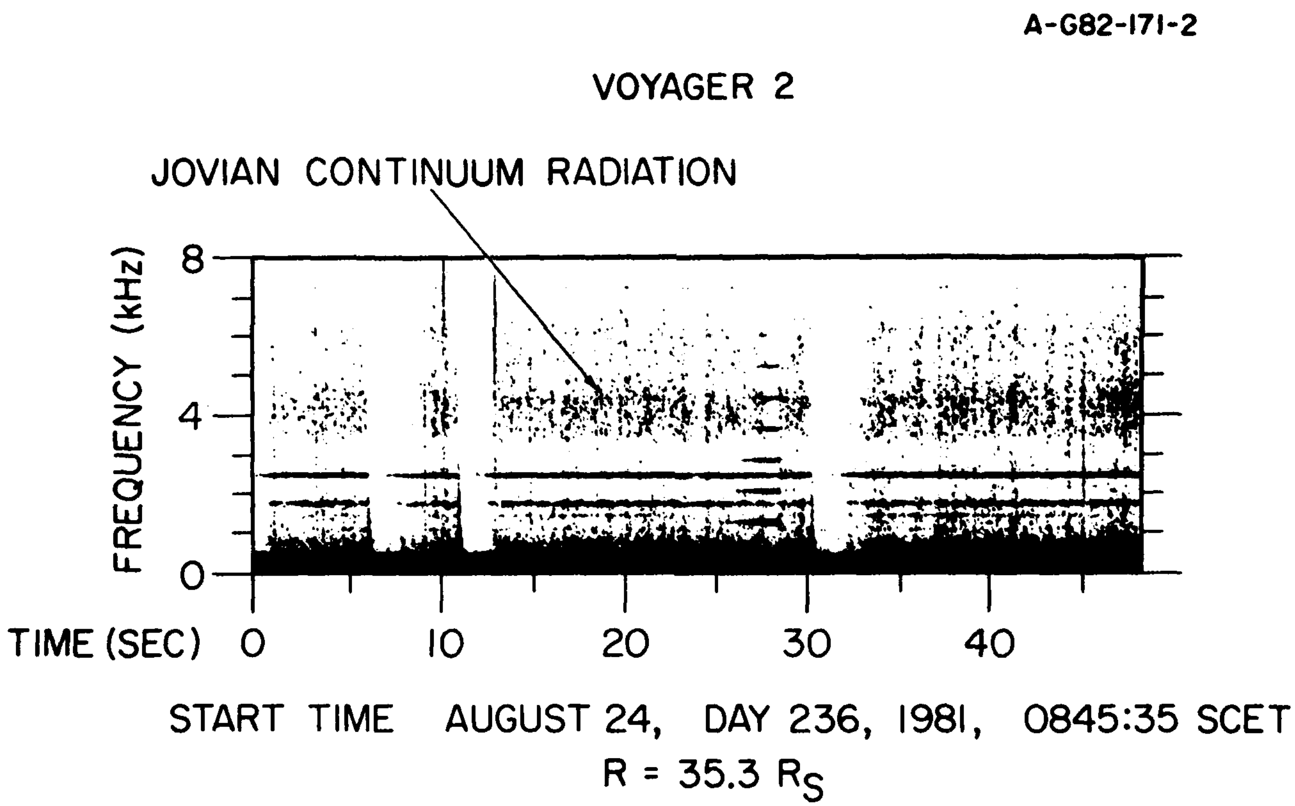
A-G82-171-2
VOYAGER 2
JOVIAN CONTINUUM RADIATION
FREQUENCY (kHz)
8
4
0
TIME (SEC) 0 10 20 30 40
START TIME AUGUST 24, DAY 236, 1981, 0845:35 SCET
R = 35.3 R_S

Figure 4

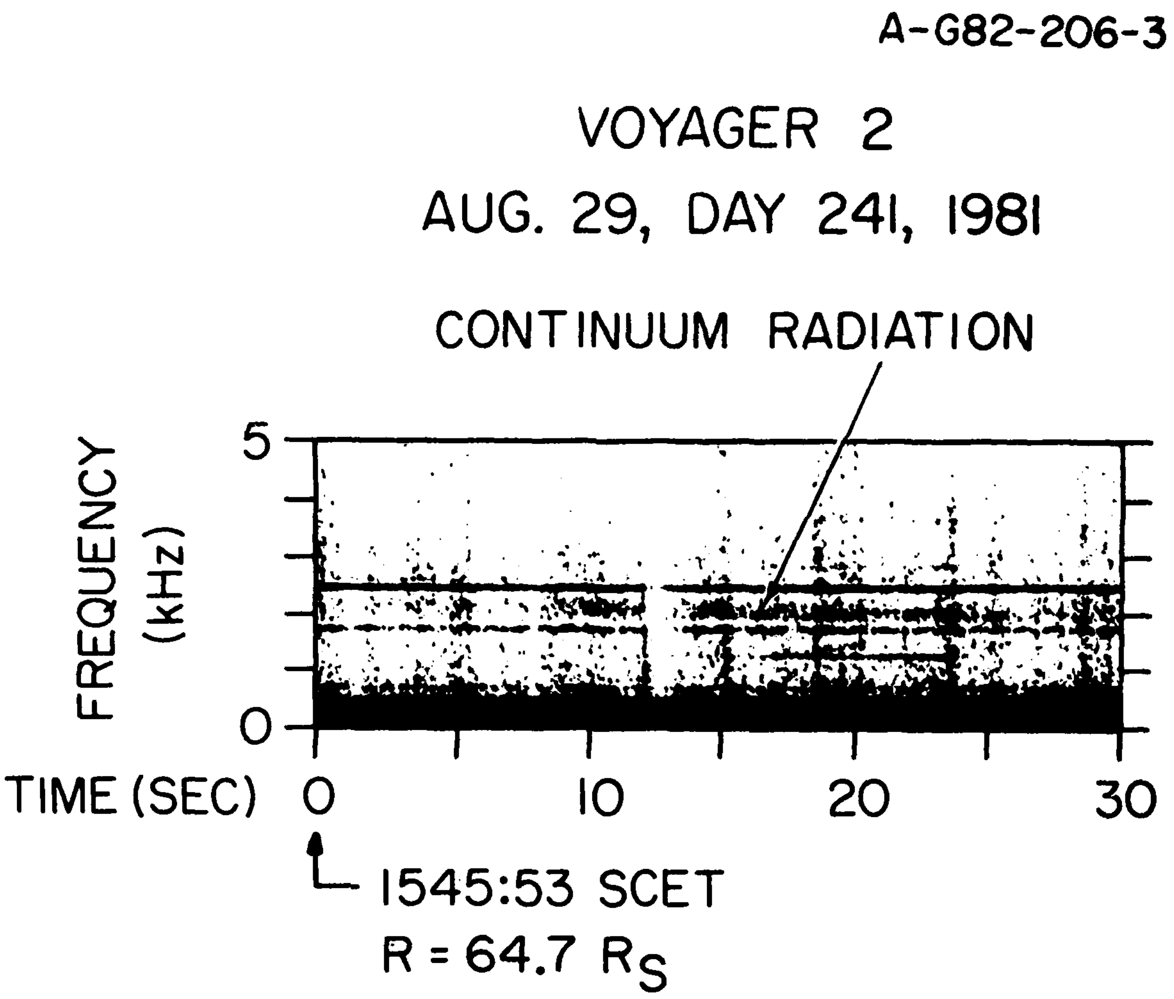
A-G82-206-3
VOYAGER 2
AUG. 29, DAY 241, 1981
CONTINUUM RADIATION
FREQUENCY (kHz)
5
0
TIME (SEC)
0
10
20
30
1545:53 SCET
R = 64.7 RS

Figure 5